STATISTICAL STUDIES OF METASTABLE LIFETIMES IN MAGNETIC MODEL SYSTEMS

by

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■ Abstract:

In this study, basically we have focused on *metastable lifetime* or the *reversal time* of magnetisation along with metastable volume fraction and different kind of metastable behaviours of ferromagnetic system. The study has been carried out particularly on Ising ferromagnet and Blume-Capel ferromagnet in presence of externally applied negative magnetic field using Monte Carlo simulation based on Metropolis dynamics. In first paper **[1]**, we have investigated the effect of quenched random field on the metastable lifetime and also on metastable volume fraction in a two dimensional Ising system. In this regard, validity of Becker-Döring theory has been checked under the influence of random field. Additionally, the dependence of reversal time on temperature as well as on strength of the random field is reported. In second paper **[2]**, the reversal of magnetisation of both the surface and bulk has been studied in a three dimensional Ising ferromagnet. A relative interfacial interaction strength (R) is considered between the surface and the core. Depending on R, an interesting competitive behaviour of surface and bulk is observed on the basis of scale of reversal time of magnetisation. In third paper **[3]**, the metastable lifetime, volume fraction and also some associated metastable behaviours in an anisotropic ferromagnet are investigated in details using Blume-Capel model. Some sort of spin dynamics have been presented in order to elucidate the effect of anisotropy. Furthermore, we report the linear dependency of the mean macroscopic reversal time on a suitably defined microscopic reversal time. In fourth paper **[4]**, the metastable behaviour of two dimensional Blume-Capel ferromagnet, under the influence of graded and step like variation of both the applied field and anisotropy, has been explored. Since both the anisotropy and the field have significant impact on the metastable lifetime, an interesting competitive scenario is obtained in a graded anisotropic system under graded field and in a step-like anisotropic system under step-like field. As a consequence, a line of marginal competition has been found out for both the cases, separating the regions of field dominated reversal and anisotropy dominated reversal. In fifth paper **[5]**, we present an investigation of the metastable lifetime of spin-s Ising and Blume-Capel models, where $s = \{1/2, 1, 3/2, 2, 5/2, 3, 7/2\}$. Both the spin-$s$ models are found to obey the Becker-Döring theory, as was initially developed for the case of $s = 1/2$ Ising ferromagnet within the classical nucleation theory. Moreover, the decay of metastable volume fraction nicely follows the Avrami's law for all values of s and for both models considered.
[1]

1 Please note, the references are indicated by red coloured bracket **[ ]** .

■ Introduction:

In the technology of magnetic recording, the magnetisation switching time plays the crucial role, to determine the speed of recording [6]. The macroscopic magnetisation switching time is significantly dependent on the microscopic reversal time or metastable lifetime of the system. Magnetic materials are used in wide variety of devices. In some cases, magnetic particles need to response to the presence of very weak magnetic field. Whereas, for better longevity of memory devices, direction of magnetisation is required to keep as stable as possible, against any type of magnetic or thermal noises. From both theoretical and technological perspective, the field induced magnetisation reversal is of great interest since many decades. A wide knowledge about the field-induced reversal of the magnetisation in various environments is surely recommended [7]. The reversal of magnetisation and the dependence of the reversal time on the applied magnetic field were historically analyzed by Becker-Döring theory (of classical nucleation) [8].

Extensive computer simulation and experimental work on the decay of metastable state and nucleation are done in last few decades. Kinetics of nucleation, particularly rate of nucleation of crystalline droplets in the solid-melt systems, dependence of lifetime of metastable state on applied field and system size, nucleation in higher dimensional system has been matter of interest [9-11]. Moreover, dynamic magnetization-reversal under a pulsed field, thermally activated magnetisation switching of small ferromagnetic particles, rates of growth and decay of the clusters of different sizes, have been studied [12-15]. The rate of nucleation of critical nuclei, its expansion speed and the corresponding changes of free energy is well connected and is described by famous Kolmogorov-Johnson-Mehl-Avrami law [16–18]. Dynamics of magnetisation reversal in models of magnetic nanoparticles and ultra-thin films have also been reported [19-23]. Nonequilibrium magnetization reversal has been investigated in Ising ferromagnet driven by periodic impulsive fields in mean-field approximations [24]. Nucleation has been studied in Ising ferromagnet under the presence of field spatially spreading in time [25]. Very recently, reversal of magnetisation by a field having gradient has been studied in Ising ferromagnet [26]. Also, magnetisation reversal in Ising ferromagnet has been explored under the influence of both the thermal and field gradient [27].

The following study regarding the behaviour of metastable lifetime has been accomplished in discrete classical spin models (spin- ½ Ising model, spin-1 Blume-Capel model, spin-*s* Ising and Blume-Capel model [28]) by extensive Monte Carlo simulation using Metropolis single spin flip algorithm [29-31]. The whole problem dates back to 1935, where the classical theory of nucleation was developed by Becker and Döring for spin- ½ Ising system, predicting the growth of supercritical droplets and also different reversal mechanisms depending on the strength of the applied field. Although the Metropolis algorithm may not be the optimum choice for studying critical properties of such spin models, but in the present work it is a safe and convenient vehicle, as we are only interested in the metastable behavior well below the critical point.

**** Classical Nucleation theory (CNT) and Becker-Döring analysis:** [32,33] Below the critical temperature T_C , under the influence of a very weak magnetic field (antiparallel to the initial spin direction), the ferromagnetic system passes through a metastable state which eventually decays to an equilibrium state. Time taken by the system to leave the metastable state is referred as '*metastable lifetime or reversal time*' of magnetisation (Fig-2a). According to the classical nucleation or droplet theory, in a spin- ½ Ising system below T_C , small droplets of down spins are

dispersed in the sea of up spins. The number of such droplets with size l (l denotes the number of spins "−1") is given by the Boltzmann distribution,

$$n_l = N e^{-\beta E_l} \quad ; \quad E_l = -2hl + \sigma l^{(d-1)/d} \tag{1}$$

where N is a normalization factor, $\beta = 1/k_B T$, k_B is the Boltzmann constant, T the temperature, and E_l the free energy (Fig-1) of a droplet formation of size l. In fact, E_l comes from the contribution of bulk and surface energies, where d is the space dimension. First term corresponds to the bulk energy required to flip l number of spins in a magnetic field h and the second term expresses the energy associated with the surface tension σ of the droplet. Clearly, an energy barrier (E_C) exists corresponding to the critical size (l_C) of the droplets.

$$l_c = \left(\frac{\sigma(d-1)}{2d|h|} \right)^d \quad ; \quad E_c = \frac{K_d \sigma^d}{h^{d-1}} \tag{2}$$

In the vicinity of E_C, an interesting dynamical phenomena is observed. Only the supercritical droplets having size $l > l_C$ will be energetically favored to grow (reducing the free energy) and

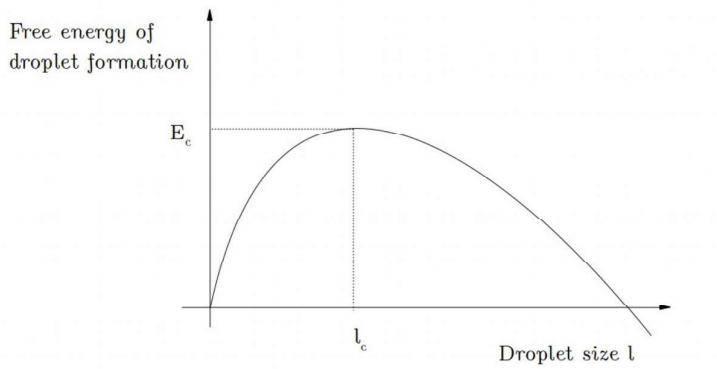

Fig-1: Schematic of free energy of formation of the droplets

eventually engulf the whole system helping the reversal of magnetization. Whereas, the subcritical droplets ($l < l_C$) are found to shrink and they are unable to take part in the reversal process. K_d is a d-dependent constant term.

Now what is the growth rate of such droplets for different strengths of the applied field? This problem was analyzed by Becker and Döring. The basic assumption of their analysis is that the time evolution of the number of droplets is only due to an evaporation-condensation mechanism in which a droplet either loses or gains a single spin without any type of coagulation or other interactions. The main result is that the nucleation rate (I) is largely dependent on E_C,

$$I = I_0 e^{-E_C/k_B T} \tag{3}$$

where I_0 is the rate prefactor. Thus, the metastable lifetime in the *nucleation regime*, τ_{nr} is obtained by,

$$\tau_{nr} \sim I^{-1} \sim \exp\left(\frac{K_d \sigma^d}{k_B T h^{d-1}}\right) \tag{4}$$

A different scenario is observed for stronger field. Many critical droplets grow simultaneously ($l^{1/d} \sim t$) and coalesce with each other resulting in complete reversal of spins. Clearly the rate of change in the magnetization is proportional to the droplet-size variation. So for a fixed change in the magnetization Δm, the metastable lifetime in *coalescence regime* is,

$$\tau_{cr} \sim I^{-\frac{1}{d+1}} \sim \exp\left(\frac{K_d \sigma^d}{k_B T (d+1) h^{d-1}}\right) \tag{5}$$

From the above description and in particular from Eqs. (4) and (5) we can securely deduce that the metastable lifetime logarithm is described by a fair straight line when depicted as a function of the

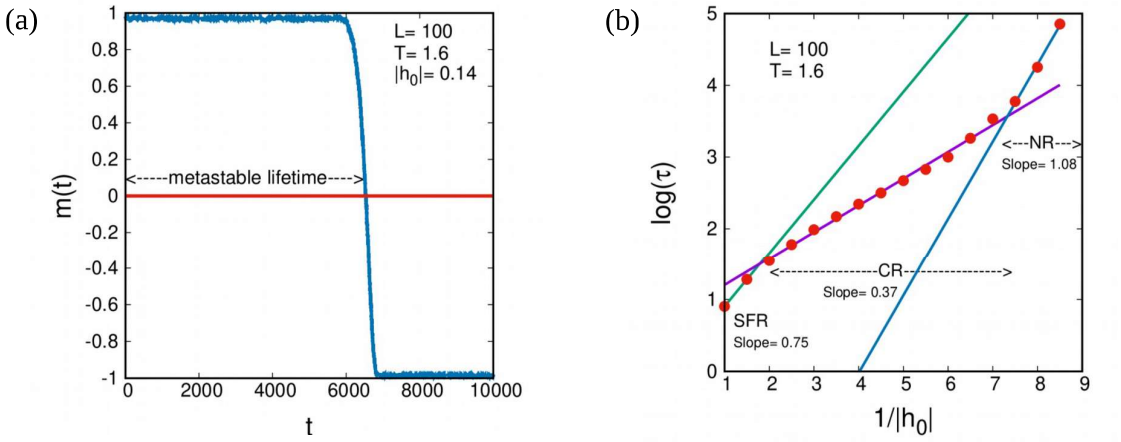

Fig-2: (a) A typical decay of metastable state (magnetisation with time) at temperature $T= 1.6\ (0.7T_C)$ in the presence of negative external field, time is in the unit of Monte Carlo step per site (MCSS), (b) logarithmic mean reversal time with inverse of field. Three different regimes namely strong field regime (SFR), coalescence regime (CR) and nucleation regime (NR) are identified.

inverse applied-field strength (Fig-**2b**). In addition to that, the slope of this line is expected to be smaller in the coalescence regime when compared to that in nucleation regime.

■ Brief description of work:

1. Effects of random fields on the reversal of magnetisation of Ising ferromagnet [1]:

The random field Ising model (RFIM) is of great interest since many decades for its ability to represent large number of impure or disordered materials [34-37]. Generally there are many interesting topic related to this model like the ferro-para phase transition, stability of ordered state, critical exponents etc. Here, we will particularly focus on metastable lifetime in presence of quenched random field. What will happen to the reversal time of a ferromagnetic system in the presence of disorder? This is a pertinent question and should be addressed to the research of the magnetisation switching phenomena. The study has been accomplished in a square Ising system considering periodic boundary condition on both directions. Three different types of statistical distribution (bimodal, uniform and Gaussian) of the random field (h_r), having zero mean, are used in addition to the uniform field (h_0). Total random field is simply $h_i = h_0 + h_r$ so that $\langle h_i \rangle = h_0$ only, since $\langle h_r \rangle = 0$.

➢ We observed that the reversal time decreases (Fig-3) in presence of any kind of random fields. Additionally, the reversal time as well as the spin configurations vary with the nature of the

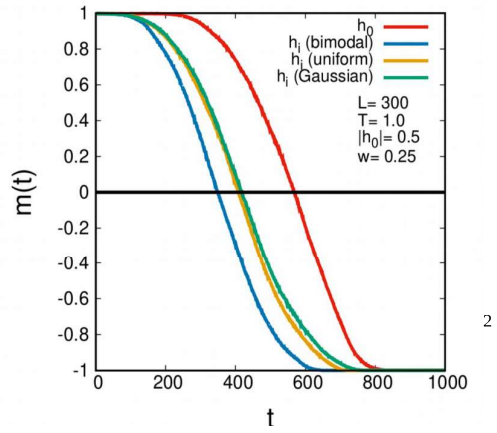

Fig-3: Variation of magnetisation (m(t)) with time (t) in presence of uniform field h_0 and also in presence of random field (h_i) (for 3 distributions of h_r). The unit of time is MCSS (Monte Carlo step per site). Strength of the random field is determined by the width of the distributions '*w*'.

distribution of random fields though the mean of each distribution is zero. Bimodal distribution is found to be more effective than the uniform or normal distribution in lowering the reversal time. The possible reason is analyzed in the paper.

➢ In presence of quenched random field, we have found that the three different regimes (namely strong field regime, coalescence regime, and nucleation regime) are still present as predicted by Becker-Döring theory (for uniform field). However, it is worth mentioning that, the nucleation

2 For details of the Hamiltonian, simulation technique, terms and notations of each work, please go through [1-5] .

regime (growth of single droplets) is found (Fig-**4**) to be affected by stronger (characterized by the width of the distribution '*w*') random field. Actually, stronger random field makes the net magnetic

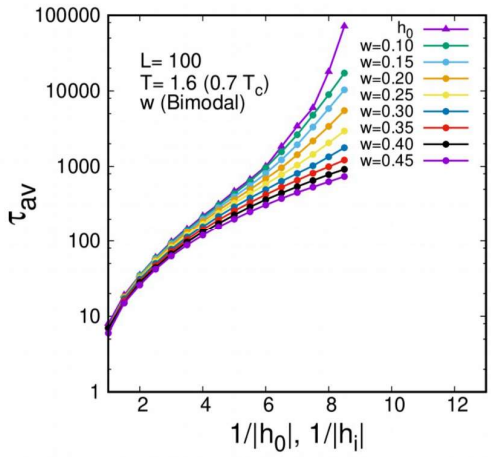

Fig-4: Variation of the mean reversal time with the inverse of field, purple line with triangular point is for uniform field only (h_0) and others are for bimodal random field (h_i).

field strongly negative at some lattice sites and positive (unable to flip spins) at other sites. Obviously, net distribution of such field would prevent to grow a single droplet. For example, in case of bimodal distribution of random field the 50% of the lattice sites will produce positive field and hence resist to grow a single droplet.

➢ The variation of reversal time with temperature (T) and the strength of random field (w) has been reported. The temperature dependence of the reversal time is like $\boldsymbol{\tau \sim exp(A/T)}$ as expected form the Becker-Döring theory. And the reversal time varies with the width (reflects the strength of the random field) of the distribution of random field as $\boldsymbol{\tau \sim exp(-Bw)}$ where A, B are constants. Immediately, it can be inferred that the strength of the random field or strength of disorder plays a similar role of temperature on metastable lifetime.

➢ It would be interesting as well as important to know the time dependence of the decay of volume fraction of up (+1) spin in the presence of quenched disorder. In the pure system, it follows Avrami's law **[16, 17, 18, 38]** which predicts that, near T_C , the metastable volume fraction (density of spin '+1') decay with time as $\exp\{-(t/\tau)^{d+1}\}$ for d dimensional system. Disordered system is also found to follow the law in well manner.

➔ As a future study, definitely one can survey the effect of random bond dilution, time varying random field etc. Moreover, the influence of non magnetic impurity can be checked by considering vacancies at some lattice sites. Other classical spin models (both 2D and 3D) can be considered also for better realizations.

2. Competitive metastable behaviours of surface and bulk in Ising ferromagnet [2]:

Magnetism of surface and interfaces has drawn much attention of the researchers due to its significant impact in the technological areas because of its divergent behaviours compared to the bulk [38-40]. In this article, an interesting competitive behaviour between surface-reversal and bulk-reversal has been studied extensively in a cubic Ising ferromagnet. The whole system is kept in open boundary conditions in all directions. The outer layers are considered as surface and the whole system as bulk. Does the surface reversal synchronize with bulk reversal? What would be the relative interaction strength for such synchronization ? These questions have been addressed here along with some additional observations.

➢ The surface interacts with the core (excluding surface) by a relative interaction strength (R). For a fixed value of the temperature (T) and applied negative magnetic field (h), the metastable lifetime of surface and bulk are found to be different (Fig-5). Both the surface and the bulk reversal times

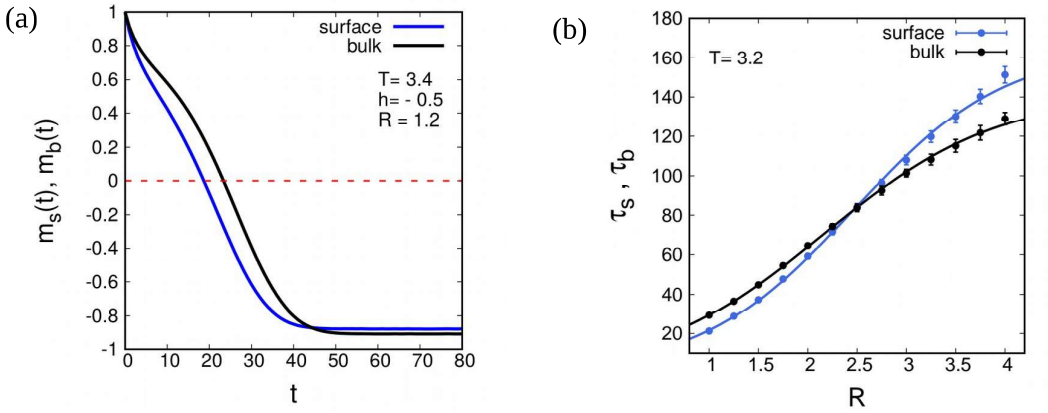

Fig-5: (a) Variation of magnetisation $m(t)$ with time t (in unit of MCSS) for relative interaction strengths $R = 1.2$. Applied field is $h = -0.5$. Lattice size= 32. (b) Variation of mean reversal time of surface τ_s and bulk τ_b with R. Intersection point indicates R_C for which $\tau_s = \tau_b$.

grow with the R as $\tau(R) = \frac{a}{1+\exp\{(b-R)/c\}}$. It was observed further that the surface reversal occurs earlier for weak interaction whereas the bulk reversal occurs earlier for strong R. Interestingly, a critical value of relative interaction strength (R_C) was found, for which both the (surface and bulk) reversal occur simultaneously.

➢ This critical relative interaction strength (R_C) (intersection of two curves in Fig-5b), was found (Fig-6) to be a function of temperature and the applied magnetic field. For fixed h, the R_C is a monotonically decreasing function of temperature. However, an interesting scaling behaviour, like $R_C \sim h^{-\beta} f(Th^{\alpha})$, was found by the method of data collapse. The 'f' is the scaling function and the estimated exponents are $\alpha = 0.23 \pm 0.01$ and $\beta = -0.06 \pm 0.01$.

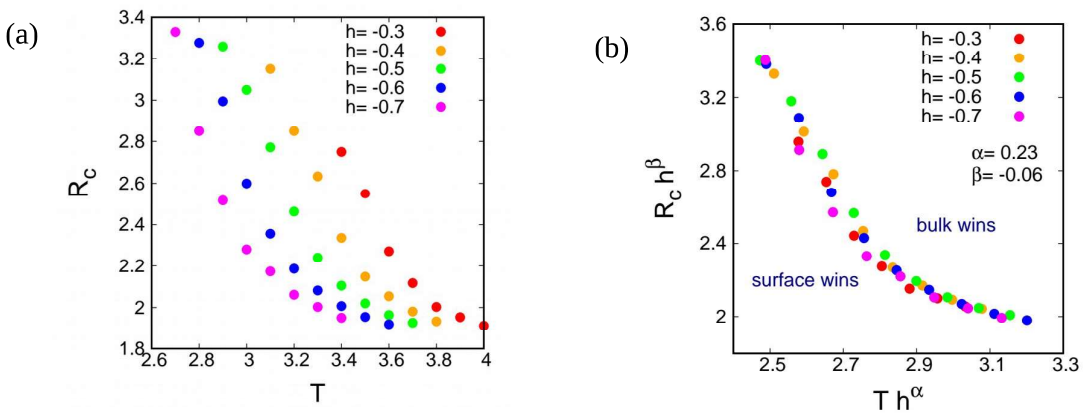

Fig-6: (a) Variation of R_C with temperature T for different strengths of field. (b) scaled data indicating a boundary of competitive behaviour of surface and bulk. Below the boundary, surface wins in faster reversal whereas above the boundary bulk wins.

➢ The critical relative interaction strength decreases monotonically with the system size L, for fixed values of the temperature (T) and applied magnetic field (h). Here, the data have been fitted $R_C \sim \exp\{b\, L^{-1.5}\}$. It is worth mentioning that, in the thermodynamic limit, the value of R_C tries to reach a fixed value $R_C \sim 2.078$.

➢ The decay of metastable volume fraction was also observed to reflect the surface and bulk metastability through Avrami's law. The metastable surface volume fraction was found to decay at $\exp\{-(t/\tau)^3\}$ and that for bulk $e\{-(t/\tau)^4\}$. These results are convincing that the bulk and surface have different metastable behaviours.

➔ In short, the surface and bulk metastable behaviours show various interesting effects, in Ising ferromagnet, which show further scopes of research. In continuation of this work, already we have a plan to study the surface reversal in an anisotropic system using Blume-Capel model.

3. Anisotropy driven reversal of magnetisation in Blume-Capel ferromagnet: A Monte Carlo study [3]:

Magnetic anisotropy plays crucial role in the technologies of magnetic memory devices. In this paper, the nature of reversal of magnetisation is studied in a square (with periodic boundary condition on both directions) anisotropic spin-*1* Blume-Capel ferromagnet **[41-45]** under the influence of externally applied magnetic field. Basically, the single-ion magneto-crystalline anisotropy is considered.

➢ The behaviour of reversal time in presence of applied field is studied (Fig-7) with both the positive and negative values of the anisotropy D. The mean reversal time is found to be exponentially decreasing with positive D (easy-plane anisotropy) and to be exponentially increasing

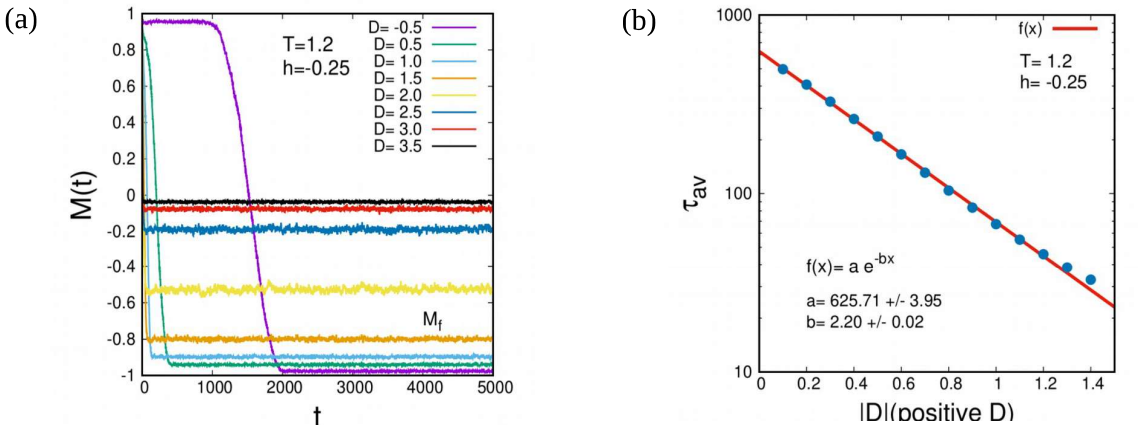

Fig-7: (a) Variation of magnetisation with time for different values of anisotropy *D* (b) variation of mean reversal time with positive anisotropy.

with the magnitude of negative *D* (easy-axis anisotropy). The standard deviation of reversal times shows an interesting behaviour. For positive *D*, it falls exponentially with the magnitude of *D*. However, the rate of falling is higher in the low anisotropy regime. In the case of negative anisotropy, a qualitatively contrast behaviour is observed.

➢ We have studied the evolution of densities of the spins '+1', '0' and '-1' in a microscopic level for better understanding of the reversal phenomena in the Blume-Capel model. The mean density ρ_0^1 , i.e. density of spin '0' (only surrounded by all '+1') is studied as function of time.

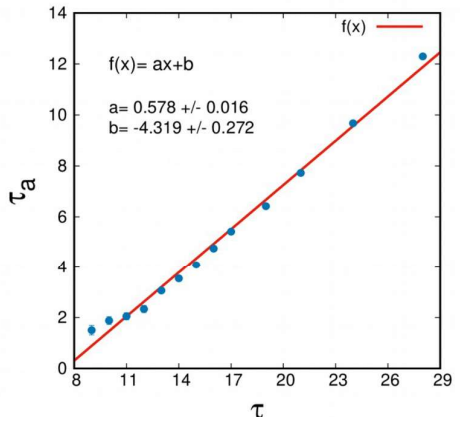

Fig-8: Relation between microscopic reversal time (τ_a) and average macroscopic reversal time τ .

ρ_0^1 decays exponentially with time. Interestingly, the suitably defined microscopic time is found to depend linearly (Fig-**8**) on the macroscopic reversal time. Moreover, the growth of mean density of spin '−1' is also checked and the effect of anisotropy has been explained by introducing a characteristic time.

➢ After the reversal, the magnetisation was observed to reach a saturated value M_f (with some fluctuation of course). M_f is found (Fig-**9**) to be strongly dependent on the strength of the *D*.

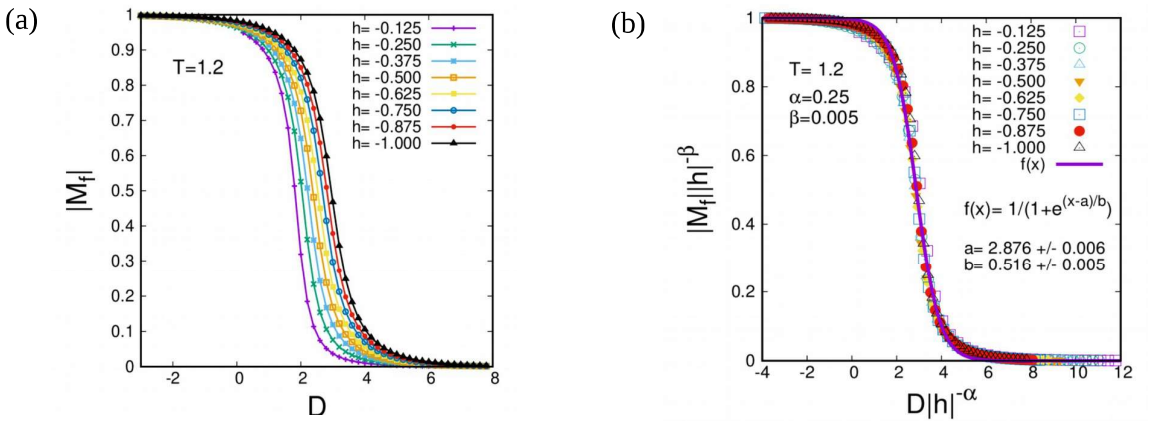

Fig-9: (a) Variation of saturated magnetisation (M_f) with anisotropy (D) for different values of applied field (h), (b) Scaled saturated magnetisation versus scaled anisotropy.

A scaling relation ' $|M_f| \sim |h|^{\beta} f(D|h|^{-\alpha})$ ' with the scaling function of the form $f(x) = 1/\{1+e^{(x-a)/b}\}$ is found out (fig-**9b**). The scaling relation was obtained in a certain range of temperature by employing the method of simple data collapse.

- Avrami's law holds good also in Blume-Capel system.

- System must suffer from the finite size effect. For that, the reversal time and its fluctuations are also checked for three different system sizes. The mean reversal time does not show any remarkable change however the standard deviation of reversal time decreases with the increase of the system size which is quite expected in general statistical analysis.

➔ The functional forms of the saturated magnetisation after reversal, depending on the anisotropy and field, are obtained from the numerical data. It would be interesting to derive those laws by analytical methods. For this reason the Becker-Döring analysis, for the growth of critical clusters, has to be extended for anisotropic Blume-Capel model. As further extension of this work, we have already started to investigate the effect of anisotropy (both spatially uniform and distributed) on metastable behaviours in Heisenberg model having continuous spin symmetry in presence of both the transverse and longitudinal field.

4. Metastability in graded and step like variation of field and anisotropy of the Blume-Capel ferromagnet [4]:

How does the metastable lifetime of a system get modified under some spatial modulation of field or anisotropy? **[46,47]** Behaviour of a uniform anisotropic system in presence of graded and step-like variation of field is studied. As well as the behaviour of a graded and step-like anisotropic system under uniform field is also checked. Finally, a competitive scenario is observed when considering a graded (step-like) anisotropic system under graded (step-like) field. The study has

been carried out in a square Blume-Capel system considering open boundary conditions on both directions.

➢ The mean reversal time is found to increase (obviously dependent on gradient's direction) in presence of graded field as compared to that for uniform field. In case of graded field, a major portion of the lattice experiences weaker magnetic field which plays the role of such delayed reversal. In addition, growth of single (and multi) nucleating cluster is noticed in some micro-lattices under weaker (and stronger) region of field, in support of Becker-Döring theory.

➢ The mean reversal time is found (Fig-**10**) to follow the $\langle\tau\rangle \sim exp(bG_h)$ with the gradient of field. A crossover in the value of the rate (b) of this exponential growth is observed from the lower value of the gradient to higher value of the gradient of the field. In the case of step-like field, a linear growth of mean reversal time is observed. For graded anisotropic system under uniform field, the mean reversal time decrease exponentially $\langle\tau\rangle \sim exp(-bG_D)$ with the gradient (G_D) of the

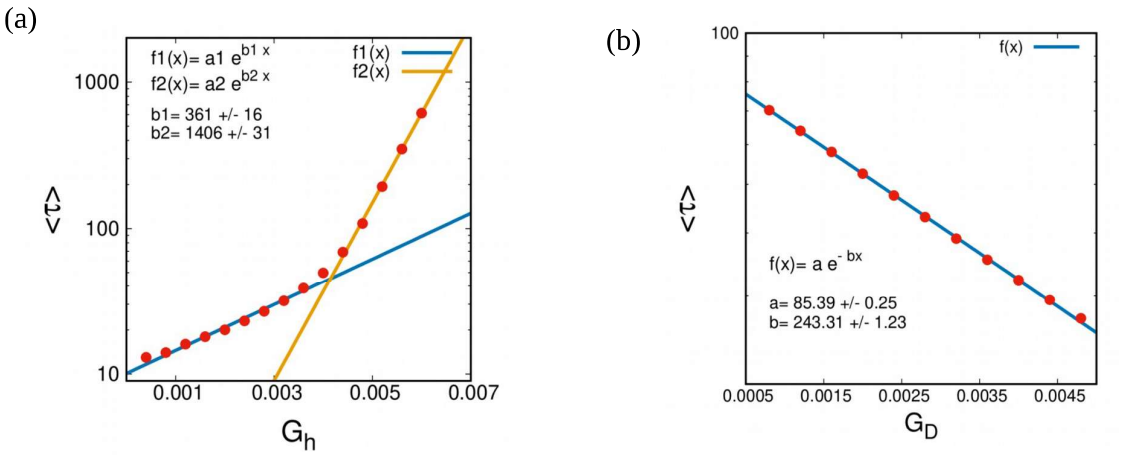

Fig-10: (a) mean reversal time ($\langle\tau\rangle$) with gradient (G_h) of graded field ; (b) mean reversal time with gradient (G_D) of graded anisotropy.

anisotropy. However, it decays in a stretched exponential manner in a step-like anisotropic system.

➢ The dependence of the mean reversal time on the system size is found to obey a scaling relation $\langle\tau\rangle \sim L^{-\beta} f(G_h L^{\alpha})$ with $\alpha \simeq 1.06$ and $\beta \simeq 0$.

➢ The nonuniform spatial variation of the mean densities of spin projections is provided in the case of graded magnetic field. The density of spin '+1' is found to decrease from left to right in contrary to that of '-1'. The density of '0' gets peaked nearly in the middle. In case of stronger field or stronger anisotropy, sharp fall of density of '+1' or sharp rise of '-1' indicates appearance of an interface. The mean numbers of spin flip also shows a nonuniform spatial variation in the case of graded magnetic field. Interestingly, for higher gradient this shows a very sharp peak in the middle. In the case of step field, this shows a finite discontinuity in the middle, clearly reflecting the stepped discontinuity of the applied magnetic field. Similar kind of behaviour is also obtained for spatial variation of anisotropy.

➢ The mean position and the roughness of the interface or domain wall is studied as function of the gradient of the applied field. Under graded field, the mean position of the domain wall is observed to shift towards right in a hyperbolic tangent fashion with the value of the gradient and the roughness of the interface of the domains decays in a stretched exponential manner. Similarly the gradient of anisotropy also influences the motion of interface.

➢ Having the knowledge of the metastable lifetimes by graded field and graded anisotropy, the joint effects of both are investigated. Interestingly, a competitive scenario (definitely dependent on the direction of gradient of both the field and anisotropy) is obtained (Fig-**11**) with the help of a suitably defined competition factor (C_F). That results in a marginal competition drawn in the plane

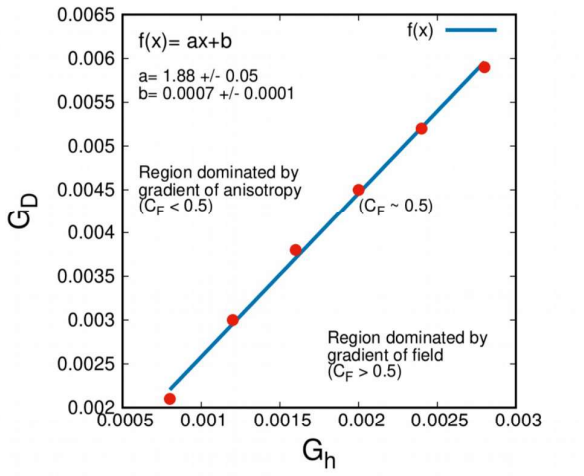

Fig-11: Gradient of anisotropy with gradient of field. The line indicates those pair of G_h and G_D which equally take part in reversal.

of gradients of field and anisotropy. The linear boundary is found to separate the regions of field dominated reversal and anisotropy dominated reversal. The joint effects of step field and step anisotropy are also investigated.

➢ The decay of metastable volume fraction is studied in the case of uniform, graded and step field to check the Avrami kind of variation. In all the cases, the logarithmic volume fractions are found to decay as $-(t/\tau)^3$ supporting Avrami behaviours. However, the decay becomes relatively slower (with smaller decay rate) after the reversal.

➢ Finally, we have studied the temperature dependence of mean reversal time across the phase boundary of first order and second order ferro-para phase transitions. We have not observed any significant change (near the transition) in the behaviour of the monotonic decrease of the reversal time as one moves from ferro to para region.

➔ In future, the study can be continued in other spin systems like general spin-s Ising model, spin-s Blume-Capel model, Potts model etc. to examine whether such systems exhibit marginal competition as well as to explore the nature of interface. In addition, other kinds of spatial modulation of field and anisotropy can be used for better presentation of reality.

5. Metastable behavior of the spin-s Ising and Blume-Capel ferromagnets: A Monte Carlo study [5]:

We present an extensive Monte Carlo investigation of the metastable lifetime through the reversal of the magnetization of spin-*s* Ising and Blume-Capel models **[48,49]**, where s = {1/2, 1, 3/2, 2, 5/2, 3, 7/2}. It remained unclear whether the Becker-Döring theory accommodates for metastability phenomena of general spin-s ferromagnetic models. We have investigated the metastable behaviour of general discrete spin-s models. However, other open questions under scrutiny include the effect of single-ion anisotropy on the reversal time of the magnetization and decay of metastable volume fraction.

➢ To explore the Becker-Döring theory, the system must simply be kept below the critical temperature. For that, the pseudo critical temperature (T_L^*) of the normalized spin system has been determined from the peak of the magnetic susceptibility. T_L^* is found to decrease with the increase

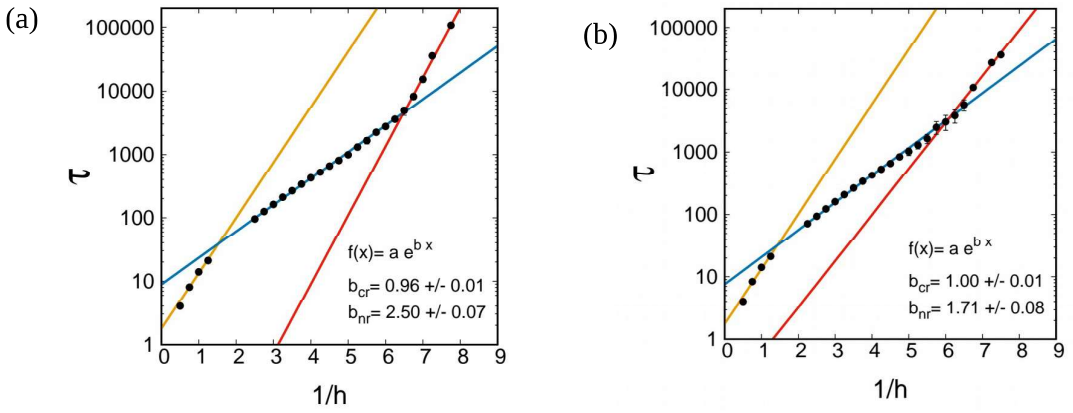

Fig-12: logarithmic mean reversal time with inverse of applied field for (a) spin-*2* and (b) spin- *5/2* Blume-Capel system. Temperature is set at $0.7T_C$.

of 's' for both the Ising and Blume-Capel system. In this context, it is obvious that, at a particular temperature and in the presence of a uniform magnetic field the reversal time is found to decrease with the increasing s.

➢ Field dependence of metastable lifetime is checked for spin-s system. In particular our Monte Carlo results for the general Ising and Blume-Capel models fully verified (Fig-**12**) predictions of the Becker-Döring theory, indicating its wide applicability to the general case of spin-s ferromagnetic models.

➢ Redefining the metastable volume as the relative abundance of the positive values of the spin projections, we studied (Fig-**13**) its variation as a function of the time for three different regimes of

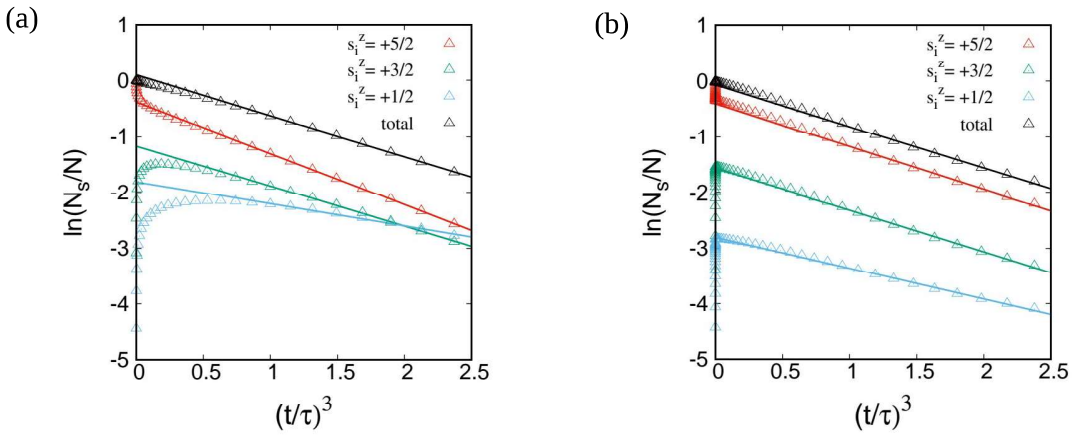

Fig-13: Variation of logarithmic density of positive component of spin projections with time at field (a) h= -0.2 (b) h= -0.8. Dimensionless time (dividing it by mean reversal time) is used for better illustration of the behaviour in the vicinity of reversal time for different strengths of field.

the applied magnetic field (weak, intermediate, and strong). In all cases, the metastable volume fraction was found to decay following the Avrami's law. Finally, many of the intriguing phenomena revealed via Monte Carlo simulations were explained using simple energetic arguments of droplet formation in the underlying theory.

➔ Noteworthy, the Ising and Blume-Capel model considered in this work have been widely used up to now in the literature for modeling various physical systems. Yet other fruitful candidates would be the general q-states Potts model and the anisotropic Heisenberg ferromagnet (having continuous spin symmetry) where compelling metastability results are expected while varying the number of spin states q and anisotropy. We plan to pursue these research lines in the near future.

■ Summary:

[1] Reversal time or metastable lifetime is reduced by applying any kind of random field. Quantitatively that reduction depends on different statistical distributions of random field. In that context bimodal distribution is more effective than uniform or Gaussian distribution of random field. Disordered system follows Becker-Döring theory of classical nucleation. But stronger disorder affect the nucleation regime. The reversal time increase exponentially with the inverse of temperature. Moreover, it decreases exponentially with the strength of the random field. The random field disorder plays a similar role of temperature.

[2] Metastable lifetime of surface and bulk is found to be different depending on the relative interfacial interaction strength (R). A critical value of R is found (R_C) for which the reversal of surface synchronizes with the bulk, such that for $R < R_C$ lifetime of surface is smaller than that of bulk and $R > R_C$ lifetime of bulk is smaller than that of surface. That R_C, temperature T and externally applied field h are connected through a scaling relation. R_C , varies with the size of the lattice, which approaches a fixed value in the large scale limit.

[3] The mean reversal time is found to be exponentially dependent on anisotropy (D). Whether it exponentially increases or decreases that is decided by the nature of the anisotropy (negative or positive). Some sort of spin dynamics has been checked. Especially, the effect of anisotropy has been elucidated by examining the growth of spin '-1' having some characteristic time. Macroscopic reversal time is found to linearly connected to the microscopic time (suitably defined by surveying the density of specific spin '0'). After the reversal, the magnetisation reaches a saturated value (with some fluctuation of course). This saturated magnetisation M_f , follows a scaling relation with anisotropy and field. Avrami's law holds good in anisotropic system. Lastly, it should be clearly mentioned that, this particular work has been carried out disregarding the ferro-para phase diagram of Blume-Capel system. Although the two dimensional Blume-Capel model shows an interesting phase diagram (of ferro-para phase transition) in the anisotropy-temperature plane, the monotonic behaviour of the reversal time does not show any discontinuity acrossing the phase boundary **[4]**. In fact, we should keep in mind that the reversal is triggered under the application of nonzero external magnetic field, which is zero in the phase diagram mentioned in this context.

[4] Reversal time can be tuned by different kinds of spatial modulation of external field. Underlying Becker-Döring theory of classical nucleation is also verified in micro lattices near the two boundaries of the system. The mean reversal time changes exponentially with the gradient of field and anisotropy. Whereas it changes linearly with the step-difference of the step-like field and stretched exponentially with step-difference of anisotropy. Stronger part of the graded field or anisotropy helps to develop an interface which moves in hyperbolic tangent fashion depending on the strength of the gradient. If we check the reversal in a graded anisotropic system by applying a magnetic field (negative) in such a way that the direction of field's gradient is along the direction of anisotropy's gradient, a marginal competition between the field and anisotropy is emerged. The metastable volume fraction, in presence of graded and step-like field, decays following Avrami's law. However, the decay becomes relatively slower (with smaller decay rate) after the reversal.

[5] For spin-s Ising and Blume-Capel systems, pseudo critical temperatures are obtained first. It decreases with increasing s. As a consequence, at a fixed temperature and applied field, reversal

time decreases with increasing *s*. Spin-*s* Ising and Blume-Capel system are found to follow Becker-Döring theory of classical nucleation which was originally proposed for Ising-1/2 system. Metastable volume fractions of both the system obey the Avrami's law. Altogether, as it became apparent from this work the system becomes more flexible for reversal as the value of *s*. Light controlled switching of magnetisation in ferromagnets having higher spin values (Fe complexes) has been highlighted very recently **[50]** .

Metastability and nucleation are very common phenomena in nature specially observed in different types of crystallization process, phase transitions between different liquid crystal phases, ferroelectrics, ferromagnets etc. Although the real materials hardly follow the Metropolis dynamics, the results, presented here, give at least a qualitative idea of metastable behaviours of ferromagnets in different environments. We expect the main conclusions of our work to be qualitatively insensitive to the use of other algorithms. And we hope that this work will pave the way for more advanced studies in this growing field of research. Very recently, the behaviour of the droplet free energy in two dimensional Ising model in the presence of randomly positioned static and dynamic impurities has been extensively studied **[51]**. Lowering of both the free energy barrier height and critical nucleus size, with increasing the impurity density for the static case, has been reported. The nucleation rates obtained from CNT and the 'Forward Flux Sampling method' for different densities of the static impurity show good agreement.

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